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***Abstract* — We present the method employed for reproducing wave energy dissipation over a vegetation field in the spectral model TOMAWAC. The method is based on the formulation proposed by Suzuki et al. (2011) that consists of implementation of the uni-directional random waves vegetation model proposed by Mendez and Losada (2004) for breaking and non-breaking waves in a full spectral model. This expression allows considering the geometric and physical characteristics of the vegetation field and is suitable for the transformation of monochromatic waves or irregular narrow banded waves. The present model, which is validated with the original equation and results from Mendez and Losada (2004), allows predicting the effects of vegetation fields on random waves. In field applications, it can then contribute to a better understanding of the impact of waves on eelgrass beds and thus, strengthen scientific knowledge necessary for the development of eelgrass bed restoration strategies.**

I. INTRODUCTION

Seagrasses are the largest submerged aquatic vegetation ecosystem protected in Europe (included in the directive 92/43/EEC). They play an important ecological role providing highly valuable ecosystem services, including coastal protection. For this reason, in recent years, numerous models have been developed to account for wave attenuation by vegetation. Some authors studied wave attenuation using the time-averaged conservation equation of wave energy, accounting for vegetation effects using an energy dissipation term (e.g. Dalrymple et al. 1984, Mendez and Losada 2004), while others use the conservation of momentum approach (Kobayashi et al. 1993, Lima et al. 2006). These models were expressed in terms of a wave shear stress friction coefficient (Teeter et al. 2001) or the drag force acting on the vegetation (Dalrymple et al. 1984, Kobayashi et al. 1993).

A popular approach for predicting wave attenuation by vegetation is the solution of the time-averaged conservation equation of wave energy in which the local flow field is estimated using linear wave theory. The effects of the vegetation are included only in the dissipation term in the energy equation used to obtain the local wave height. Theoretically, the depth-integrated energy dissipation rate per unit bed area is defined as

$$\varepsilon_v = \int_0^{h_v} \left(F_x u_x + F_y u_y + F_z u_z \right) dz \tag{1}$$

where F_i and u_i are the components of force $\vec{F}$ [N] and velocity $\vec{u}$ [m/s] ($i = x$, y and z), and h_v [m] is the vegetation height.

Dalrymple et al. (1984) examined wave diffraction due to localized areas of energy dissipation, such as dense stands of kelp, pile clusters, or submerged trees, and derived an energy dissipation factor based on the Morison equation (1950). As an approximation, a vegetation stem (such as a tree trunk) is conceptualized as a cylinder. The total force exerted on a vegetation element is the sum of a drag force and an inertia force, as expressed by the Morison equation (Morison et al. 1950):

$$\vec{F} = \frac{1}{2} C_D \rho A_v |\vec{u}| \vec{u} + C_M \rho V_v \frac{d\vec{u}}{dt} \tag{2}$$

where $\vec{F}$ [N] is the total force on the vegetation element, C_D [-] is the drag coefficient, C_M [-] is the inertia coefficient, ρ [kg/m^3] is the water density, A_v [m] is the projected area defined as the frontal area of the vegetation element projected to the plane normal to the streamwise flow direction, V_v [m^3] is the volume of a vegetation element, and $\vec{u}$ [m/s] is the vector of flow velocity acting on the vegetation element.

Mendez and Losada (2004) present an extension of the Dalrymple formulation that includes the possibility for vegetation parameterization and can handle sloping bottom conditions and breaking waves as well. This approach more closely represents the physical processes within a vegetation field, since it takes into account the diameter, density and height of the vegetation in the calculation of the bulk drag coefficient. This model was further adapted by Suzuki et al. (2011), who extended Mendez and Losada's formulation to multiple frequencies and directions.

In the next sections, we present the implementation of the wave dissipation model of Suzuki et al. (2011) in TOMAWAC (sections II and III), the model validation (section IV) and, in the conclusion, a discussion of the numerical results (section V).

II. Wave Dissipation Model

The energy of waves propagating through vegetation (e.g. kelp bed, salt marshes, mangrove trees) is dissipated because of the work done by the vegetation. Assuming that linear wave theory is valid and considering regular waves normally incident on a coastline with straight and parallel contours, the conservation of energy equation is reduced to

$$\frac{\partial E c_g}{\partial x} = -\varepsilon_v \tag{3}$$

Where E [N/m] is the wave energy, c_g [m/s] is the group velocity, x [m] is the onshore coordinate and ε_v [N/m².s] is the time-averaged energy dissipation per unit horizontal area induced by the vegetation.

For a given vegetation field, the conventional definition for the depth-integrated and time-averaged energy dissipation (Eq. 1) per horizontal area unit can be expressed by:

$$\varepsilon_v = \overline{\int_{-h}^{-h+\alpha h} FU dz} \tag{4}$$

Where, αh is the mean vegetation height, h [m] is the water depth, the over-bar stands for time average over a wave period, $\boldsymbol{F}=(F_x,0,F_z)$ [N] is the force acting on the vegetation per unit volume and $\boldsymbol{U}=(u,0,w)$ [m/s] is the velocity for the 2D case.

According to Kobayashi et al. (1993), Dubi and Torum (1997) and Mendez and Losada (1999), in an anisotropic dissipative medium such as the vegetation field, the term $F_z w$ is negligible in comparison with $F_x u$. Therefore, Eq. 4 can be simplified to:

$$\varepsilon_v = \overline{\int_{-h}^{-h+\alpha h} F_x u dz} \tag{5}$$

Neglecting swaying motion and inertial forces (Dalrymple et al., 1984, Kobayashi et al., 1993), plant-induced forces acting on the fluid can be expressed in terms of a Morison-type equation. Therefore, Eq. 2 is reduced in terms of the horizontal force per unit volume to:

$$\vec{F}_x = \frac{1}{2} C_D \rho b_v N_v |u| u \tag{6}$$

Where b_v [m] is the stem diameter of cylinder (plant), N_v [-] is the number of plants per square meter and u [m/s] is the horizontal velocity due to wave motion. Based on Eq. 5 and Eq. 6, Dalrymple's formula for energy dissipation as presented by Mendez and Losada (2004) reads

$$\varepsilon_v = \frac{2}{3\pi} \rho C_D b_v N_v \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(k\alpha h)} H^3 \tag{7}$$

In which H [m] is the wave height, σ [s^{-1}] is the wave frequency and k [m^{-1}] is the wave number.

This formula was modified by Mendez and Losada (2004) to enable the estimation of wave dissipation by vegetation for narrow-banded random waves. The wave height

$$\langle \varepsilon_v \rangle = \frac{1}{2\sqrt{\pi}} \rho \tilde{C}_D b_v N_v \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(k\alpha h)} H_{rms}^3 \tag{8}$$

With $\tilde{C}_D$ being a bulk drag coefficient that may be dependent on the Keulegan – Carpenter (KC) number.

III. Implementation in TOMAWAC

TOMAWAC (Benoit et al., 1996) is a scientific software which models the changes, both in time and in the spatial domain, of the power spectrum of wind-driven waves for applications in the oceanic domain, in intracontinental seas, as well as in the coastal zone. TOMAWAC models the sea state by solving the balance equation of the action density directional spectrum. Thus, the model reproduces the evolution of the action density directional spectrum at each node of a spatial computational grid.

In TOMAWAC, the wave directional spectrum is split into a finite number of propagation frequencies f_i and directions θ_j. The balance equation of wave action density is solved for each component (f_i, θ_j). The model is said to be a third generation model (e.g. like the WAM model [WAMDI, 1988] [Komen et al., 1994]), since it does not require any parameterization of the spectral or directional distribution of power (or action density).

The action density spectrum $N(\sigma,\theta)$ is given by the formula

$$N(\sigma,\theta) = \frac{F(\sigma,\theta)}{\sigma} \tag{9}$$

Where the relative frequency σ [s^{-1}], as observed from a frame of reference moving with the current velocity, and the wave direction θ [rad] are the independent variables with F [m²/Hz] being the variance density spectrum. The evolution of the wave spectrum is described by the spectral action balance equation which, for Cartesian coordinates, is given by:

$$\begin{gathered}\frac{d}{dt}N(\sigma,\theta) + \frac{d}{dx}c_x N(\sigma,\theta) + \frac{d}{dy}c_y N(\sigma,\theta) \\ + \frac{d}{d\sigma}c_\sigma N(\sigma,\theta) + \frac{d}{d\theta}c_\theta N(\sigma,\theta) = \frac{S_{tot}}{\sigma}\end{gathered} \tag{10}$$

Where the first term represents the local rate of change of N in time, the second and the third terms represent propagation in the x and y directions, with velocities c_x and c_y. The fourth term represents the shifting of the relative frequency due to variations in water depth and currents, while the fifth term represents depth induced refraction. The right hand side is the energy source term, which accounts for the generation and dissipation of waves, and non-linear interactions between waves. The model accounts for wave propagation in space including shoaling and refraction, dissipation by bottom friction $S_{ds,b}$, white-capping $S_{ds,wc}$ and depth-induced breaking $S_{ds,br}$, wave-growth due to wind input S_{in}, and energy transfer within the spectrum due to non-linear wave-wave interactions such as quadruplets S_{nl4} and triads S_{nl3}. The latter six processes contribute to S_{tot}:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,b} + S_{ds,wc} + S_{ds,br} \tag{11}$$

According to Suzuki et al. (2011), to include wave damping due to vegetation, Eq. 11 will be extended with $S_{ds,veg}$ by expanding Eq. 8 to include frequencies and directions as follows

$$S_{ds,veg}(\sigma,\theta) = \frac{D_{tot}}{E_{tot}} F(\sigma,\theta) \tag{12}$$

With

$$D_{tot} = -\frac{1}{2g\sqrt{\pi}} \tilde{C}_D b_v N_v \left(\frac{\tilde{k}g}{2\tilde{\sigma}}\right)^3 \frac{\sinh^3(\tilde{k}\alpha h) + 3\sinh(\tilde{k}\alpha h)}{3\tilde{k}\cosh^3(\tilde{k}h)} H_{rms}^3 \tag{13}$$

Where the mean frequency $\tilde{\sigma}$, the mean wave number $\tilde{k}$ and the total wave energy E_{tot} are defined as (WAMDI Group, 1988):

$$\tilde{\sigma} = \left(E_{tot}^{-1} \int_0^{2\pi}\int_0^{\infty} \frac{1}{\sigma} F(\sigma,\theta) d\sigma d\theta \right)^{-1} \tag{14}$$

$$\tilde{k} = \left(E_{tot}^{-1} \int_0^{2\pi}\int_0^{\infty} \frac{1}{\sqrt{k}} F(\sigma,\theta) d\sigma d\theta \right)^{-2} \tag{15}$$

$$E_{tot} = \int_0^{2\pi}\int_0^{\infty} \frac{1}{\sigma} F(\sigma,\theta) d\sigma d\theta \tag{16}$$

With $H_{rms}^3 = 8E_{tot}$, the final expression reads:

$$S_{ds,veg}(\sigma,\theta) = -\sqrt{\frac{2}{\pi}} \tilde{C}_D b_v N_v \left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3 \frac{\sinh^3(\tilde{k}\alpha h) + 3\sinh(\tilde{k}\alpha h)}{3\tilde{k}\cosh^3(\tilde{k}h)} \sqrt{E_{tot}} F(\sigma,\theta) \tag{17}$$

IV. MODEL VALIDATION

The present model is validated with the original equation and results from Mendez and Losada (2004) for non-breaking and breaking uni-directional random waves.

A. Non-breaking uni-directional random waves

The random wave transformation model for a flat bottom by Mendez and Losada (2004) is expressed as follows.

$$H_{rms} = \frac{H_{rms,o}}{1+\tilde{\beta}x} \tag{18}$$

With

$$\tilde{\beta} = \frac{1}{3\sqrt{\pi}} \tilde{C}_D b_v N_v H_{rms,o} k \frac{\sinh^3 k\alpha h + 3\sinh k\alpha h}{(\sinh 2kh + 2kh)\sinh kh} \tag{19}$$

where $H_{rms,o}$ is the value of root mean square wave height at the wave boundary x=0.

Simulations were carried out with a water depth h = 2.0 m and a constant peak wave period T_p (1, 2, 4, 6, 8 and 10 seconds) and root mean square wave height $H_{rms,o}$ (0.4 m) at the incident wave boundary. The vegetation height was taken as equal to the water depth (αh = 2.0 m), the plant area per unit height was b_v = 0.04 m, the number of plants per unit area was N = 10 units/m², and the bulk drag coefficient was $\tilde{C}_D = 1.0$. The vegetation was present in the entire computational domain.

The computational domain was composed of a flat (slope = 0.0) 2D grid with an aspect ratio of 1 (cross-shore direction):10 (along shore direction). The calculation grid size was set as 2.0 m in the wave propagation direction.

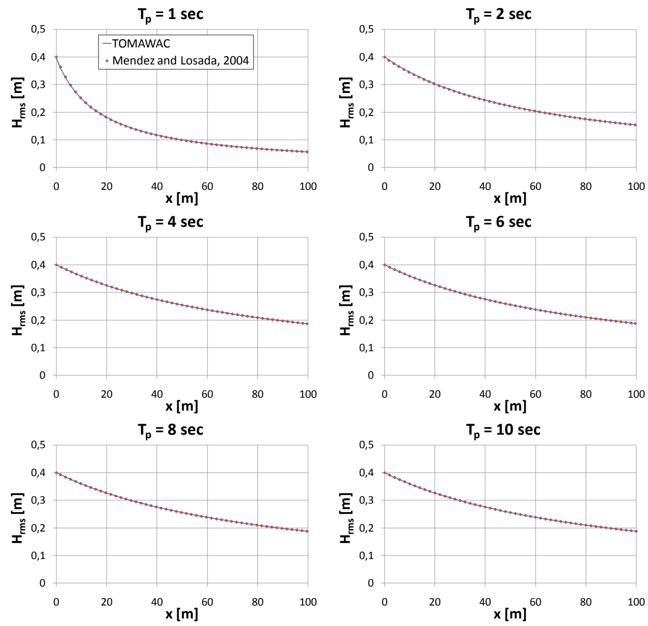

Figure 1. Comparison of H_{rms} evolution for numerical wave model (TOMAWAC) and random wave transformation model (Mendez and Losada, 2004)

Fig. 1 shows very good agreement between the results obtained with the random wave transformation model by Mendez and Losada (2004) and the formulation implemented in TOMAWAC. Thus, TOMAWAC is able to reproduce the same wave attenuation as with the random wave transformation model for non-breaking uni-directional random waves.

B. *Breaking uni-directional random waves*

In order to carry out an analysis of the influence of plant height, vegetation field width and breaking on the propagation, Mendez and Losada (2004) analysed the evolution of the wave height over a Dean's shape profile (Dean, 1991) defined as follow:

$$h = 0.25 \cdot (300 - x)^{2/3} \tag{20}$$

Where h [m] is the water depth, 0.25 the sediment scale parameter, and *x=0* in the offshore boundary. According to the authors, the incident wave conditions imposed to TOMAWAC on the offshore boundary are given by $H_{rms,o}$ = 2.5 m (equivalent to significant wave height H_s = 3.54 m) and T_p = 10 s. Two vegetation heights, d_v = 1 and 3 m and a single 100 m long vegetation field, from 50 to 150 m, are used. The number of plants per square meter is N = 20 units/m² and the plant area per unit height of vegetation is b_v = 0.25 m. The bulk drag coefficient was $\tilde{C}_D = 0.2$. The incident waves are uni-directional random waves as defined in the previous section and the breaking model used is that of Thornton and Guza (1983) with γ = 0.6 (where the parameter γ is the proportional control factor indicating the maximum water depth "H_m" compatible with water depth "d": $H_m = \gamma d$). The computational domain is the same as for test 1. The results from Mendez and Losada (2004) and TOMAWAC model are compared in Fig. 2 below.

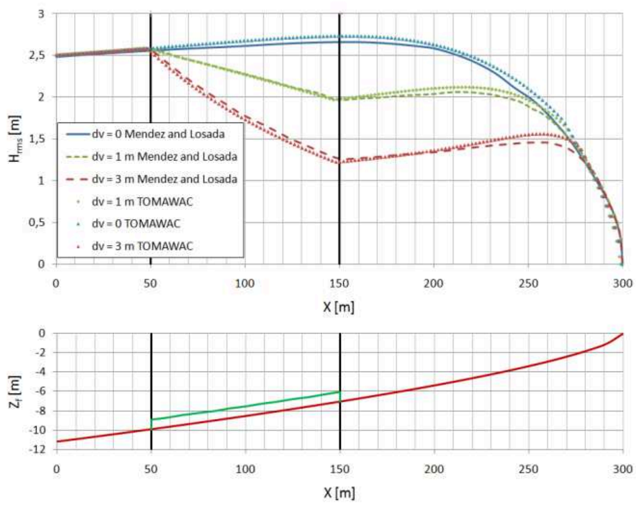

Figure 2. Comparison of H_{rms} evolution for numerical wave model (TOMAWAC) and random wave transformation model (Mendez and Losada, 2004) over Dean's shape profile.

The results show very good agreement between the Mendez and Losada model and TOMAWAC. We notice that differences seem very small and we can thus conclude that TOMAWAC is able to reproduce the same wave attenuation as with the random wave transformation model for breaking uni-directional random waves.

V. Discussion and Conclusions

We implemented in TOMAWAC a source term to take into account the spectral wave energy dissipation induced by bottom vegetation. This term comes from the extension of the theoretical model developed by Mendez and Losada (2004) for uni-directional random waves to full spectrum by Suzuki et al. (2011). The model was tested and validated for breaking and non-breaking waves by comparing the numerical results obtained with TOMAWAC with some results reported in Mendez and Losada (2004).

The two tests also allowed gaining a better understanding of some possible effects of the bed vegetation on waves. In particular, Fig.1 shows that, for a given vegetation field, the damping effects related to the vegetation are more important at higher frequencies. This is showed by the variation in space of the root-mean-square wave height H_{rms} that is directly correlated to wave energy. The maximum reduction of H_{rms} obtained for a wave period T_p = 1 s (of about 0.35 m) is much greater than the reduction of H_{rms} obtained for larger periods (i.e. for T_p = 2 s, the maximum damping is about 0.25 m and for peak periods higher than 4 seconds the damping is about 0.2 m).

Fig. 2 shows that the influence of vegetation on wave propagation depends not only on the plant height, but also on the vegetation field width. Increasing the plant height results in larger wave energy dissipation since the drag force (or the energy dissipation term) increases. Moreover, wider vegetation fields result in greater wave height reduction. Besides, the damping caused by vegetation reduces root-mean-square wave height, causing wave breaking to occur farther onshore. The geometrical properties of the vegetation field thus play an important role in wave transformation.

In conclusion, the implementation of the spectral vegetation model in TOMAWAC can be a useful tool for developing coastal restoration or/and protection strategies. In fact, the model has now the ability to calculate two-dimensional wave dissipation over a vegetation field including some important aspects such as breaking (as used in TOMAWAC). If good vegetation data are available (b_v, d_v, N), the bulk drag coefficient is the only parameter in the wave model that needs to be calibrate in order to quantify the effects of bed vegetation on random waves. This is "quite simple" if field measurements of random waves are available.

However, if data for the model calibration are not available, it must be noted that the value of the bulk drag coefficient depends on the flow around the plants and on the plant motion, which depend on the hydrodynamic and biomechanical characteristics of the plants. For this reason, many authors propose empirical equations of the bulk drag coefficient as a function of the Reynolds number or Keulegan-Carpenter number (see a detailed review in Mendez et al., 1999 or Mendez and Losada, 2004).

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